



Implications of LHC searches for Higgs-portal dark matter

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ABSTRACT

The search for the a Standard Model Higgs boson at the LHC is reaching a critical stage as the possible mass range for the particle has become extremely narrow and some signal at a mass of about 125 GeV is starting to emerge. We study the implications of these LHC Higgs searches for Higgs-portal models of dark matter in a rather model independent way. Their impact on the cosmological relic density and on the direct detection rates are studied in the context of generic scalar, vector and fermionic thermal dark matter particles. Assuming a sufficiently small invisible Higgs decay branching ratio, we find that current data, in particular from the XENON experiment, essentially exclude fermionic dark matter as well as light, i.e. with masses below ≈ 60 GeV, scalar and vector dark matter particles. Possible observation of these particles at the planned upgrade of the XENON experiment as well in collider searches is discussed.

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1. Introduction

The ATLAS and CMS Collaborations have recently reported on the search of the Standard Model (SM) Higgs boson with 5 fb^{-1} data [1]. Higgs bosons have been excluded in a significant mass range and, ignoring the unlikely possibility of a very heavy particle, only the very narrow window $m_h \approx 115\text{--}130$ GeV is now left over. There is even a slight excess of events in the data which could correspond to an SM like Higgs boson with a mass of 125 ± 1 GeV. Although the statistics are not sufficient for the experiments to claim discovery, one is tempted to take this piece of evidence seriously and analyze its consequences.

In this Letter, we study the implications of these LHC results for Higgs-portal models of dark matter (DM). The Higgs sector of the SM enjoys a special status since it allows for a direct coupling to the hidden sector that is renormalizable. Hence, determination of the properties of the Higgs boson would allow us to gain information about the hidden world. The latter is particularly important in the context of dark matter since hidden sector particles can be stable and couple very weakly to the SM sector, thereby offering a viable dark matter candidate [2]. In principle, the Higgs boson could decay into light DM particles which escape detection [3]. However, given the fact that the ATLAS and CMS signal is close to what one expects for a Standard Model-like Higgs particle, there

is little room for invisible decays. In what follows, we will assume that 10% is the upper bound on the invisible Higgs decay branching ratio, although values up to 20% will not significantly change our conclusions.

We adopt a model independent approach and study generic scenarios in which the Higgs-portal DM is a scalar, a vector or a Majorana fermion. We first discuss the available constraints on the thermal DM from WMAP and current direct detection experiments, and show that the fermionic DM case is excluded while in the scalar and vector cases, one needs DM particles that are heavier than about 60 GeV. We then derive the direct DM detection rates to be probed by the XENON100-upgrade and XENON1T experiments. Finally, we discuss the possibility of observing directly or indirectly these DM particles in collider experiments and, in particular, we determine the rate for the pair production of scalar particles at the LHC and a high-energy e^+e^- collider.

2. The models

Following the model independent approach of Ref. [4], we consider the three possibilities that dark matter consists of real scalars S , vectors V or Majorana fermions χ which interact with the SM fields only through the Higgs-portal. The stability of the DM particle is ensured by a Z_2 parity, whose origin is model-dependent. For example, in the vector case it stems from a natural parity symmetry of abelian gauge sectors with minimal field content [5]. The relevant terms in the Lagrangians are

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HS} H^\dagger H S^2,$$

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$$\begin{aligned}\Delta\mathcal{L}_V &= \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu, \\ \Delta\mathcal{L}_f &= -\frac{1}{2}m_f \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi}\chi.\end{aligned}\quad (1)$$

Although in the fermionic case above the Higgs–DM coupling is not renormalizable, we still include it for completeness. The self-interaction terms S^4 in the scalar case and the $(V_\mu V^\mu)^2$ term in the vector case are not essential for our discussion and we will ignore them. After electroweak symmetry breaking, the neutral component of the doublet field H is shifted to $H^0 \rightarrow v + h/\sqrt{2}$ with $v = 174$ GeV and the physical masses of the DM particles will be given by

$$\begin{aligned}M_S^2 &= m_S^2 + \frac{1}{2}\lambda_{hSS}v^2, \\ M_V^2 &= m_V^2 + \frac{1}{2}\lambda_{hVV}v^2, \\ M_f &= m_f + \frac{1}{2}\frac{\lambda_{hff}}{\Lambda}v^2.\end{aligned}\quad (2)$$

In what follows, we summarize the most important formulas relevant to our study. Related ideas and analyses can be found in [6–9] and more recent studies of Higgs-portal scenarios have appeared in [10,11].

The relic abundance of the DM particles is obtained through the s -channel annihilation via the exchange of the Higgs boson. For instance, the annihilation cross section into light fermions of mass m_{ferm} is given by

$$\begin{aligned}\langle\sigma_{\text{ferm}}^S v\rangle &= \frac{\lambda_{hSS}^2 m_{\text{ferm}}^2}{16\pi} \frac{1}{(4M_S^2 - m_h^2)^2}, \\ \langle\sigma_{\text{ferm}}^V v\rangle &= \frac{\lambda_{hVV}^2 m_{\text{ferm}}^2}{48\pi} \frac{1}{(4M_V^2 - m_h^2)^2}, \\ \langle\sigma_{\text{ferm}}^f v\rangle &= \frac{\lambda_{hff}^2 m_{\text{ferm}}^2}{16\pi} \frac{M_f^2}{\Lambda^2} \frac{1}{(4M_f^2 - m_h^2)^2},\end{aligned}\quad (3)$$

where v is the DM relative velocity. The cross section for Majorana fermion annihilation was computed in [12] in a similar framework. We should note that in our numerical analysis, we take into account the full set of relevant diagrams and channels, and we have adapted the program micrOMEGAs [13] to calculate the relic DM density.

The properties of the dark matter particles can be studied in direct detection experiments. The DM interacts elastically with nuclei through the Higgs boson exchange. The resulting nuclear recoil is then interpreted in terms of the DM mass and DM–nucleon cross section. The spin-independent DM–nucleon interaction can be expressed as [4]

$$\begin{aligned}\sigma_{S-N}^{SI} &= \frac{\lambda_{hSS}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2}, \\ \sigma_{V-N}^{SI} &= \frac{\lambda_{hVV}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2}, \\ \sigma_{f-N}^{SI} &= \frac{\lambda_{hff}^2}{4\pi \Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2},\end{aligned}\quad (4)$$

where m_N is the nucleon mass and f_N parameterizes the Higgs–nucleon coupling. The latter subsumes contributions of the light quarks (f_L) and heavy quarks (f_H), $f_N = \sum f_L + 3 \times \frac{2}{27} f_H$. There exist different estimations of this factor and in what follows we will use the lattice result $f_N = 0.326$ [14] as well as the MILC results [15] which provide the minimal value $f_N = 0.260$ and the

maximal value $f_N = 0.629$. We note that the most recent lattice evaluation of the strangeness content of the nucleon [16] favors f_N values closer to the lower end of the above range. In our numerical analysis, we have taken into account these lattice results, which appear more reliable than those extracted from the pion–nucleon cross section.

If the DM particles are light enough, $M_{\text{DM}} \lesssim \frac{1}{2}m_h$, they will appear as invisible decay products of the Higgs boson. For the various cases, the Higgs partial decay widths into invisible DM particles are given by

$$\begin{aligned}\Gamma_{h \rightarrow SS}^{\text{inv}} &= \frac{\lambda_{hSS}^2 v^2 \beta_S}{64\pi m_h}, \\ \Gamma_{h \rightarrow VV}^{\text{inv}} &= \frac{\lambda_{hVV}^2 v^2 m_h^3 \beta_V}{256\pi M_V^4} \left(1 - 4\frac{M_V^2}{m_h^2} + 12\frac{M_V^4}{m_h^4}\right), \\ \Gamma_{h \rightarrow \chi\chi}^{\text{inv}} &= \frac{\lambda_{hff}^2 v^2 m_h \beta_f^3}{32\pi \Lambda^2},\end{aligned}\quad (5)$$

where $\beta_X = \sqrt{1 - 4M_X^2/m_h^2}$. We have adapted the program HDECAY [17] which calculates all Higgs decay widths and branching ratios to include invisible decays.

3. Astrophysical consequences

The first aim of our study is to derive constraints on the various DM particles from the WMAP satellite [18] and from the current direct detection experiment XENON100 [19], and to make predictions for future upgrades of the latter experiment, assuming that the Higgs boson has a mass $m_h = 125$ GeV and is approximately SM-like such that its invisible decay branching ratio is smaller than 10%; we have checked that increasing this fraction to 20% does not change our results significantly.

In Fig. 1, we delineate the viable parameter space for the Higgs-portal scalar DM particle. The area between the two solid (red) curves satisfies the WMAP constraint, with the dip corresponding to resonant DM annihilation mediated by the Higgs exchange. We display three versions of the XENON100 direct DM detection bound corresponding to the three values of f_N discussed above. The dash-dotted (brown) curve around the Higgs pole region represents $\text{BR}^{\text{inv}} = 10\%$ such that the area to the left of this line is excluded by our constraint $\text{BR}^{\text{inv}} < 10\%$. The prospects for the upgrade of XENON100 (with a projected sensitivity corresponding to 60,000 kg d, 5–30 keV and 45% efficiency) and XENON1T are shown by the dotted lines.

We find that light dark matter, $M_{\text{DM}} \lesssim 60$ GeV, violates the bound on the invisible Higgs decay branching ratio and thus is excluded. This applies in particular to the case of scalar DM with a mass of 5–10 GeV considered, for instance, in Ref. [8]. On the other hand, heavier dark matter, particularly for $M_{\text{DM}} \gtrsim 80$ GeV, is allowed by both BR^{inv} and XENON100. We note that almost the entire available parameter space will be probed by the XENON100-upgrade. The exception is a small resonant region around 62 GeV, where the Higgs–DM coupling is extremely small.

In the case of vector Higgs-portal DM, the results are shown in Fig. 2 and are quite similar to the scalar case. WMAP requires the Higgs–DM coupling to be almost twice as large as that in the scalar case. This is because only opposite polarization states can annihilate through the Higgs channel, which reduces the annihilation cross section by a factor of 3. The resulting direct detection rates are therefore somewhat higher in the vector case. Note that for DM masses below $m_h/2$, only very small values $\lambda_{hVV} < \mathcal{O}(10^{-2})$ are allowed if $\text{BR}^{\text{inv}} < 10\%$.

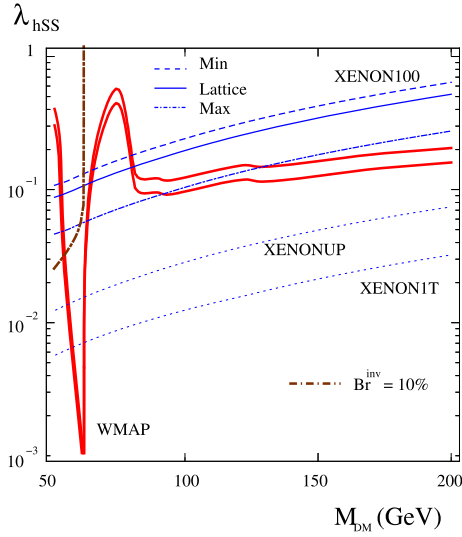


Fig. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $Br^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

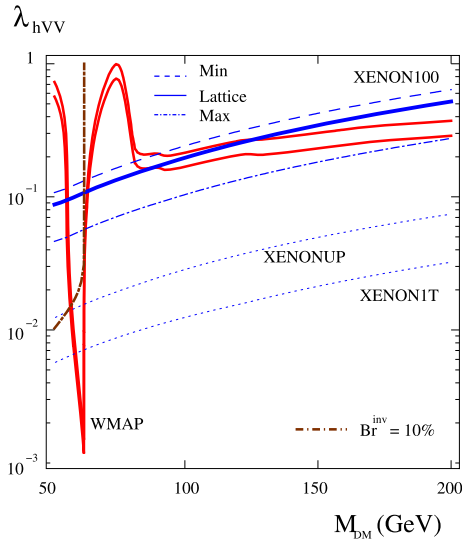


Fig. 2. Same as Fig. 1 for vector DM particles.

Similarly, the fermion Higgs-portal results are shown in Fig. 3. We find no parameter regions satisfying the constraints, most notably the XENON100 bound, and this scenario is thus ruled out for $\lambda_{hff}/\Lambda \gtrsim 10^{-3}$.

This can also be seen from Fig. 4, which displays predictions for the spin-independent DM–nucleon cross section σ_{SI} (based on the lattice f_N) subject to the WMAP and $Br^{inv} < 10\%$ bounds. The upper band corresponds to the fermion Higgs-portal DM and is excluded by XENON100. On the other hand, scalar and vector DM are both allowed for a wide range of masses. Apart from a very small region around $\frac{1}{2}m_h$, this parameter space will be probed by XENON100-upgrade and XENON1T. The typical value for the scalar σ_{SI} is a few times 10^{-9} pb, whereas σ_{SI} for vectors is larger by a factor of 3 which accounts for the number of degrees of freedom.

4. Dark matter production at colliders

The next issue to discuss is how to observe directly the Higgs-portal DM particles at high energy colliders. There are essentially

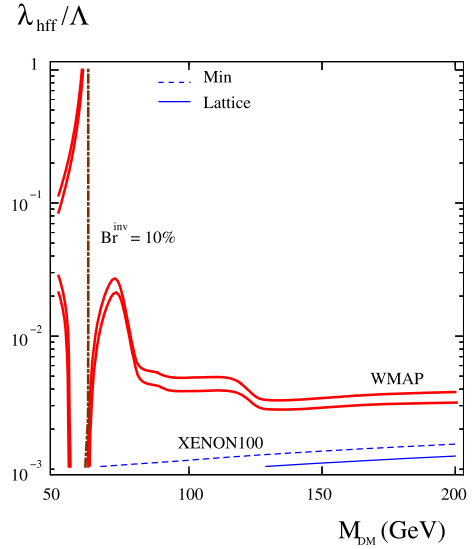


Fig. 3. Same as in Fig. 1 for fermion DM; λ_{hff}/Λ is in GeV^{-1} .

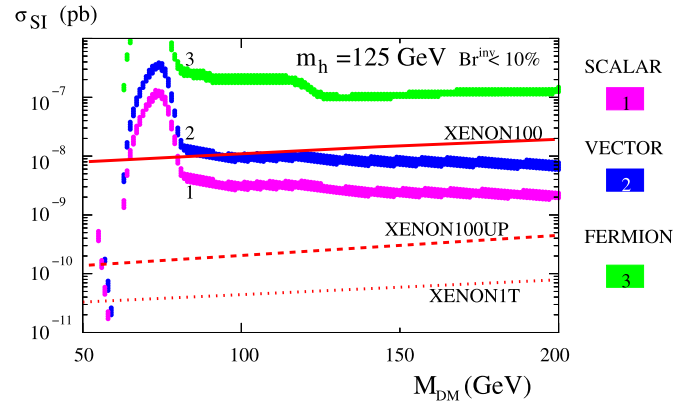


Fig. 4. Spin independent DM–nucleon cross section versus DM mass. The upper band (3) corresponds to fermion DM, the middle one (2) to vector DM and the lower one (1) to scalar DM. The solid, dashed and dotted lines represent XENON100, XENON100-upgrade and XENON1T sensitivities, respectively.

two ways, depending on the Higgs versus DM particle masses. If the DM particles are light enough for the invisible Higgs decay to occur, $M_{DM} \lesssim \frac{1}{2}m_h$, the Higgs cross sections times the branching ratios for the visible decays will be altered, providing indirect evidence for the invisible decay channel. In the case of the LHC, a detailed analysis of this issue has been performed in Ref. [7] for instance and we have little to add to it. Nevertheless, if the invisible Higgs branching ratio is smaller than $\approx 10\%$, its observation would be extremely difficult in view of the large QCD uncertainties that affect the Higgs production cross sections, in particular in the main production channel, the gluon fusion mechanism $gg \rightarrow h$ [20]. In fact, the chances of observing indirectly the invisible Higgs decays are much better at a future e^+e^- collider. Indeed, it has been shown that, at $\sqrt{s} \approx 500$ GeV collider with 100 fb^{-1} data, the Higgs production cross sections times the visible decay branching fractions can be determined at the percent level [21,22].

The DM particles could be observed directly by studying associated Higgs production with a vector boson and Higgs production in vector boson fusion with the Higgs particle decaying invisibly. At the LHC, parton level analyses have shown that, although extremely difficult, this channel can be probed at the 14 TeV upgrade with a sufficiently large amount of data [23] if the fraction of in-

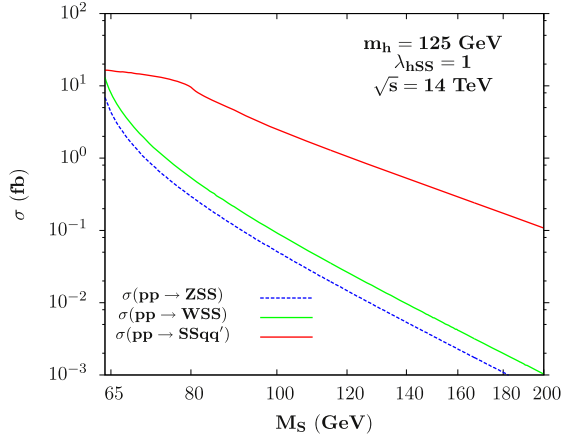


Fig. 5. Scalar DM pair production cross sections at the LHC with $\sqrt{s} = 14$ TeV as a function of their mass for $\lambda_{hSS} = 1$ in the processes $pp \rightarrow ZSS$, WSS and $pp \rightarrow W^*W^* + Z^*Z^* \rightarrow SSqq$.

visible decays is significant. A more sophisticated ATLAS analysis has shown that only for branching ratios above 30% that a signal can be observed at $\sqrt{s} = 14$ TeV and 10 fb^{-1} data in the mass range $m_h = 100\text{--}250$ GeV [24]. Again, at a 500 GeV e^+e^- collider, invisible decays at the level of a few percent can be observed in the process $e^+e^- \rightarrow hZ$ by simply analyzing the recoil of the leptonically decaying Z boson [21,22].

If the DM particles are heavy, $M_{\text{DM}} \gtrsim \frac{1}{2}m_h$, the situation becomes much more difficult and the only possibility to observe them would be via their pair production in the continuum through the s -channel exchange of the Higgs boson. At the LHC, taking the example of the scalar DM particle S , three main processes can be used: (a) double production with Higgs-strahlung from either a W or a Z boson, $q\bar{q} \rightarrow V^* \rightarrow VSS$ with $V = W$ or Z , (b) the WW/ZZ fusion processes which lead to two jets and missing energy $qq \rightarrow V^*V^*qq \rightarrow SSqq$ and (c) the gluon–gluon fusion mechanism which is mainly mediated by loops of the heavy top quark that couples strongly to the Higgs boson, $gg \rightarrow h^* \rightarrow SS$.

The third process, $gg \rightarrow SS$, leads to only invisible particles in the final state, unless some additional jets from higher order contributions are present and reduce the cross section [25] and we will ignore it here. For the two first processes, following Ref. [26] in which double Higgs production in the SM and its minimal supersymmetric extension has been analyzed, we have calculated the production cross sections. The exact matrix elements have been used in the $q\bar{q} \rightarrow ZSS, WSS$ processes while in vector boson fusion, we have used the longitudinal vector boson approximations and specialized to the $W_L W_L + Z_L Z_L \rightarrow SS$ case which is expected to provide larger rates at the highest energy available at the LHC i.e. $\sqrt{s} = 14$ TeV (the result obtained in this way is expected to approximate the exact result within about a factor of two for low scalar masses and very high energies); the analytical expressions are given in Appendix A.

As can be seen from Fig. 5 where the cross sections are shown as a function of M_{DM} for $\lambda_{hSS} = 1$, the rates at $\sqrt{s} = 14$ TeV are at the level of 10 fb in the $WW + ZZ \rightarrow SS$ process for $M_h \lesssim 120$ GeV and one order of magnitude smaller for associated production with W and Z bosons. Thus, for both processes, even before selection cuts are applied to suppress the backgrounds, the rates are small for DM masses of order 100 GeV and will require extremely high luminosities to be observed.

Again, the chances of observing DM pair production in the continuum might be higher in the cleaner environment of e^+e^- collisions. The two most important production processes in this context, taking again the example of a scalar DM particle, are

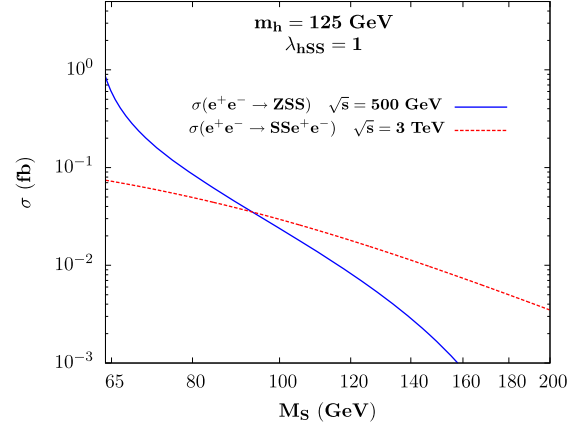


Fig. 6. Scalar DM pair production cross sections at e^+e^- colliders as a function of the DM mass for $\lambda_{hSS} = 1$ in the processes $e^+e^- \rightarrow ZSS$ at $\sqrt{s} = 500$ GeV and $ZZ \rightarrow SS$ at $\sqrt{s} = 3$ TeV.

$e^+e^- \rightarrow ZSS$ that dominates at relatively low energies and $e^+e^- \rightarrow Z^*Z^*e^+e^- \rightarrow e^+e^-SS$ which becomes important at high energies. The rate for WW fusion is one order of magnitude larger but it leads to a fully invisible signal, $e^+e^- \rightarrow W^*W^*\nu\bar{\nu} \rightarrow \nu\bar{\nu}SS$. Following again Ref. [26], we have evaluated the cross sections for $e^+e^- \rightarrow ZSS$ at $\sqrt{s} = 500$ GeV (the energy range relevant for the ILC) and for $Z_L Z_L \rightarrow SS$ at $\sqrt{s} = 3$ TeV (relevant for the CERN CLIC) and the results are shown in Fig. 6 as a function of the mass M_S for $\lambda_{hSS} = 1$. One observes that the maximal rate that one can obtain is about 10 fb near the Higgs pole in ZSS production and which drops quickly with increasing M_S . The process $ZZ \rightarrow SS$ becomes dominant for $M_S \gtrsim 100$ GeV, but the rates are extremely low, below $\approx 0.1 \text{ fb}$.

The situation should be similar in the case of vector and fermion DM and we refrain from discussing it here.

5. Conclusion

We have analyzed the implications of the recent LHC Higgs results for generic Higgs-portal models of scalar, vector and fermionic dark matter particles. Requiring the branching ratio for invisible Higgs decay to be less than 10%, we find that the DM-nucleon cross section for electroweak-size DM masses is predicted to be in the range $10^{-9}\text{--}10^{-8} \text{ pb}$ in almost all of the parameter space. Thus, the entire class of Higgs-portal DM models will be probed by the XENON100-upgrade and XENON1T direct detection experiments, which will also be able to discriminate between the vector and scalar cases. The fermion DM is essentially ruled out by the current data, most notably by XENON100. Furthermore, we find that light Higgs-portal DM $M_{\text{DM}} \lesssim 60$ GeV is excluded independently of its nature since it needs a large invisible Higgs decay branching ratio, which should be incompatible with the production of an SM-like Higgs boson at the LHC. Finally, it will be difficult to observe the DM effects by studying Higgs physics at the LHC. Such studies can be best performed in Higgs decays at the planned e^+e^- colliders. However, the DM particles have pair production cross sections that are too low to be observed at the LHC and eventually also at future e^+e^- colliders unless very high luminosities are made available.

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Appendix A

The differential cross section for the pair production of two scalar particles in association with a Z boson, $e^+e^- \rightarrow ZSS$, after the angular dependence is integrated out, can be cast into the form ($\nu = 174$ GeV):

$$\frac{d\sigma(e^+e^- \rightarrow ZSS)}{dx_1 dx_2} = \frac{G_F^3 M_Z^2 \nu^4}{384\sqrt{2}\pi^3 s} \frac{(\hat{a}_e^2 + \hat{v}_e^2)}{(1 - \mu_Z)^2} \lambda_{hSS}^2 \mathcal{Z}, \quad (\text{A.1})$$

where the electron- Z couplings are defined as $\hat{a}_e = -1$ and $\hat{v}_e = -1 + 4\sin^2\theta_W$, $x_{1,2} = 2E_{1,2}/\sqrt{s}$ are the scaled energies of the two scalar particles, $x_3 = 2 - x_1 - x_2$ is the scaled energy of the Z boson; the scaled masses are denoted by $\mu_i = M_i^2/s$. In terms of these variables, the coefficient \mathcal{Z} may be written as

$$\mathcal{Z} = \frac{1}{4} \frac{\mu_Z(x_3^2 + 8\mu_Z)}{(1 - x_3 + \mu_Z - \mu_h)^2}. \quad (\text{A.2})$$

The differential cross section has to be integrated over the allowed range of the x_1, x_2 variables; the boundary condition is

$$\left| \frac{2(1 - x_1 - x_2 + 2\mu_S - \mu_Z) + x_1 x_2}{\sqrt{x_1^2 - 4\mu_S}\sqrt{x_2^2 - 4\mu_S}} \right| \leq 1. \quad (\text{A.3})$$

For the cross section at hadron colliders, i.e. for the process $q\bar{q} \rightarrow ZSS$ one has to divide the amplitude squared given above by a factor 3 to take into account color sum/averaging, replace e by q (with $a_q = 2I_q^3$, $v_q = 2I_q^3 - 4e_q \sin^2\theta_W$ with I_q^3 and e_q for isospin and electric charge) and the c.m. energy s by the partonic one \hat{s} ; one has then to fold the obtained partonic cross section with the quark/antiquark luminosities. The extension to the $q\bar{q} \rightarrow WSS$ case (with $a_q = v_q = \sqrt{2}$) is straightforward.

For the vector boson fusion processes, one calculates the cross sections for the $2 \rightarrow 2$ processes $V_L V_L \rightarrow SS$ in the equivalent longitudinal vector boson approximation and then fold with the V_L spectra to obtain the cross section the entire processes $e^+e^- \rightarrow SS\ell\ell$ and $qq \rightarrow qqSS$; see Ref. [26] for details. Taking into account only the dominant longitudinal vector boson contribution, denoting by $\beta_{V,S}$ the V, S velocities in the c.m. frame, $\hat{s}^{1/2}$ the invariant energy of the VV pair, the corresponding cross section of the subprocess $V_L V_L \rightarrow SS$ reads

$$\hat{\sigma}_{V_L V_L} = \frac{G_F^2 M_V^4 \nu^4}{4\pi \hat{s}} \lambda_{hSS}^2 \frac{\beta_S}{\beta_W} \left[\frac{1 + \beta_W^2}{1 - \beta_W^2} \frac{1}{(\hat{s} - M_h^2)} \right]^2. \quad (\text{A.4})$$

The result obtained after folding with the vector boson spectra is expected to approximate the exact result within about a factor of two for low scalar masses and very high energies.

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